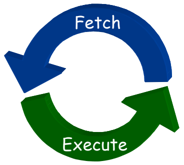
6.5 TOY Machine Architecture

The TOY Machine

Combinational circuits. ALU.
Sequential circuits. Memory.
Machine architecture. Wire components together to make computer.

TOY machine.

- 256 16-bit words of memory.
- 16 16-bit registers.
- 1 8-bit program counter.
- 16 instruction types.



TOY-Lite machine.

- 16 10-bit words of memory.
- 4 10-bit registers.
- 1 4-bit program counter.
- 16 instruction types.

How To Design a Device

How to design a device.

- Design interface: input buses, output buses, control wires.
- Determine major components.
- Determine datapath requirements: "flow" of bits.
- Establish sequencing of control.

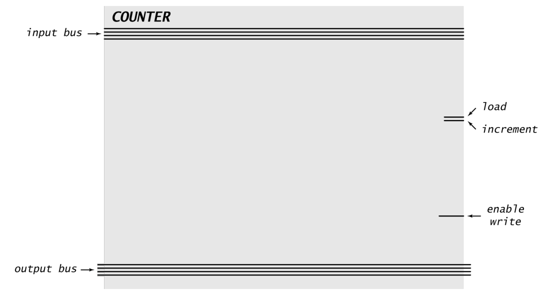
Goal. Design TOY-Lite computer.
Warmup. Design a program counter.

Build a Counter: Interface

Counter. Holds value that represents a binary number.

- Load: set value from input bus.
- Increment: add one to value.
- Value doesn't change until write enable is asserted.

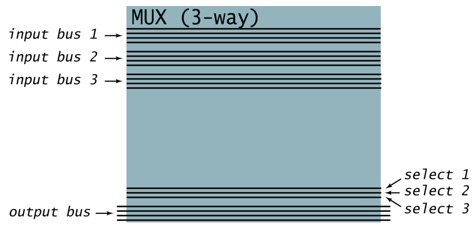
Ex. TOY-Lite program counter (4-bit).



Build a Counter: Identify Components

Components.
- Register.
- Incrementer.
- Challenge: needs connections to two different inputs. (load and increment)

Multiplexer. Combinational circuit that selects among input buses.
- Exactly one select line i is activated.
- Copies bits from input bus i to output bus.



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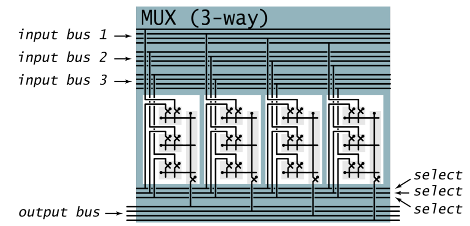
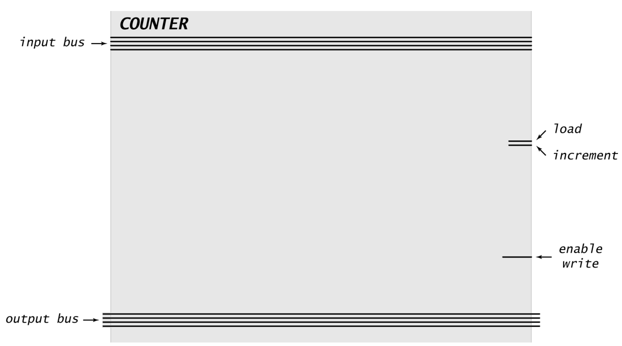


Build a Counter: Datapath and Control

Datapath.
- Layout and interconnection of components.
- Connect input and output buses.

Control. Choreographs the "flow" of information on the datapath.



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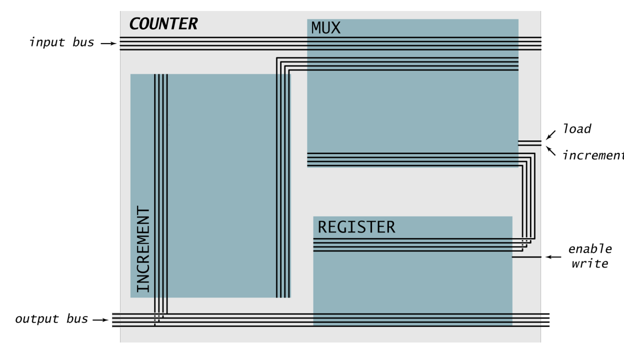

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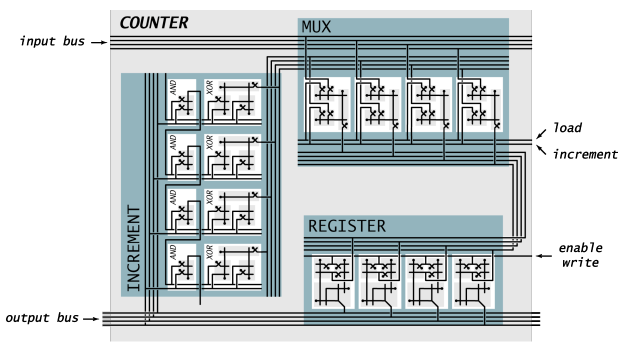
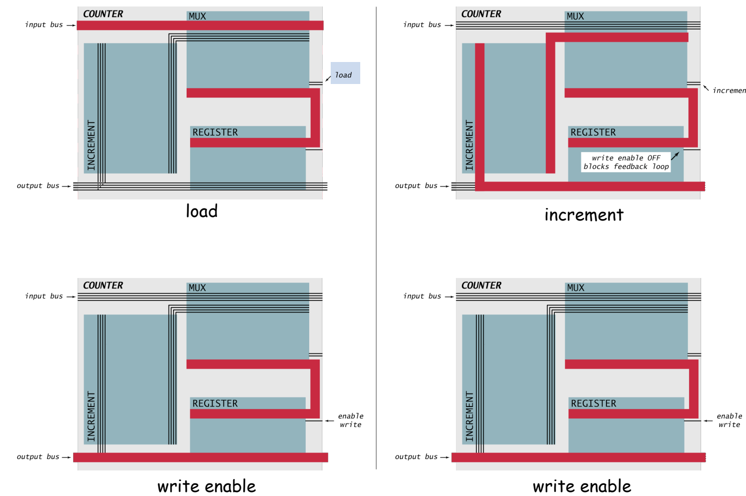


Build a Counter: Control Sequencing



How To Design a Device

How to design a device.
- Design interface: input buses, output buses, control wires.
- Determine major component devices.
- Determine datapath requirements: "flow" of bits.
- Establish sequencing of control.

Warmup. Design a program counter (3 devices, 3 control wires).

Goal. Design TOY-Lite computer (10 devices, 20 control wires).

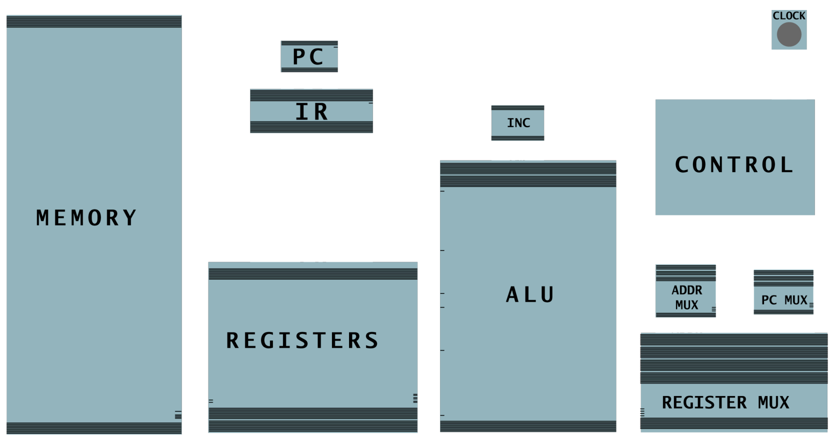
Build a TOY: Interface

Instruction set architecture (ISA).
- Determine set of primitive instructions.
  - too narrow ⇒ cumbersome to program
  - too broad ⇒ cumbersome to build hardware
- TOY family of machine: 16 instructions.
  - TOY: 16-bit words, 256 words of memory, 16 registers.
  - TOY-Lite: 10-bit words, 16 words of memory, 4 registers.

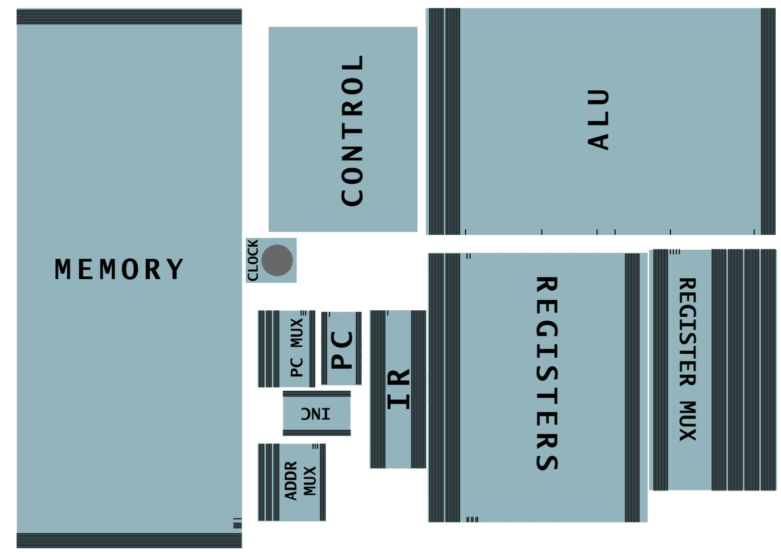
Instructions	
0:	halt
1:	add
2:	subtract
3:	and
4:	xor
5:	shift left
6:	shift right
7:	load address

Instructions	
8:	load
9:	store
A:	load indirect
B:	store indirect
C:	branch zero
D:	branch positive
E:	jump register
F:	jump and link

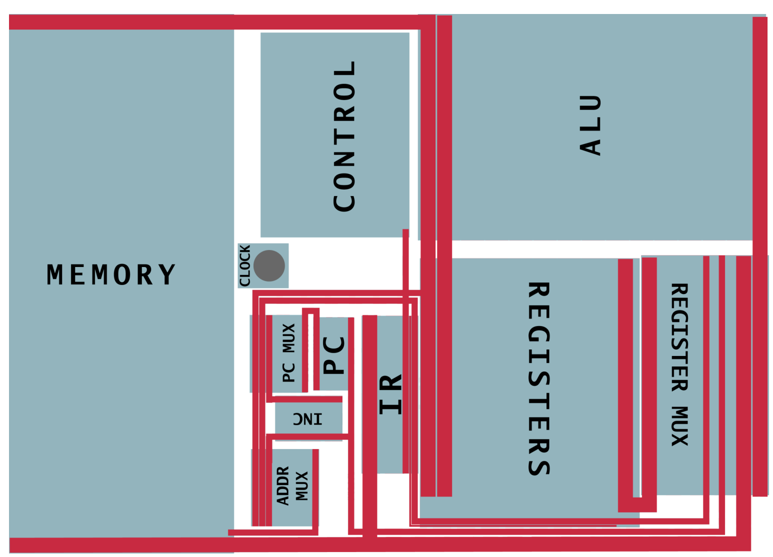
Build a TOY-Lite: Devices



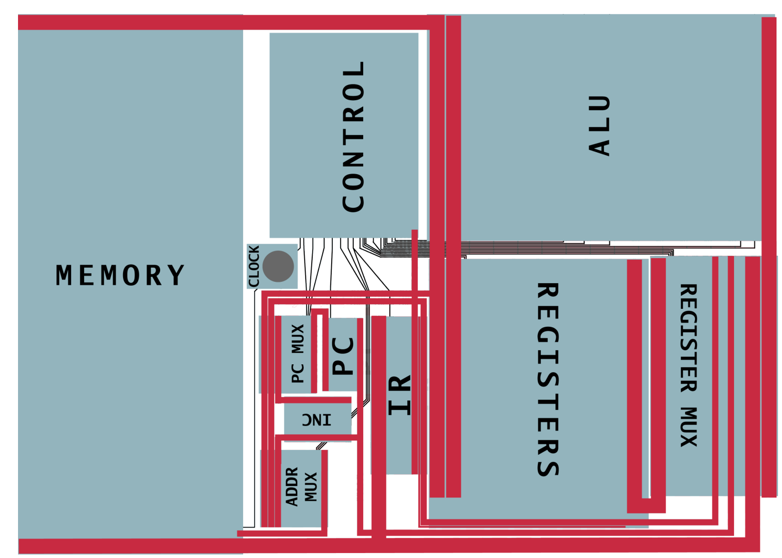
Build a TOY-Lite: Layout



Build a TOY-Lite: Datapath



Build a TOY-Lite: Control



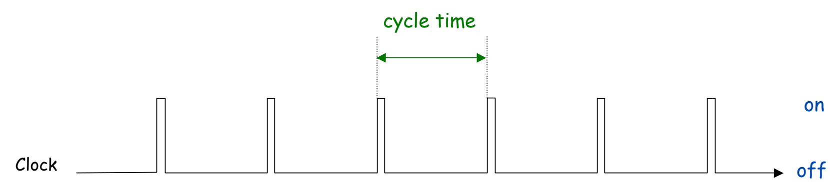
Control

Control. Each instruction corresponds to a sequence of control signals.

Q. How do we create the sequence?
A. Need a clock.

Clock

Clock.
- Fundamental abstraction: regular on-off pulse.
  - on: fetch phase
  - off: execute phase
- External analog device.
- Synchronizes operations of different circuit elements.
- Requirement: clock cycle longer than max switching time.



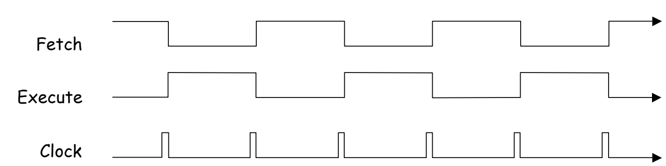
How much does it Hert?

Frequency is inverse of cycle time.
- Expressed in hertz.
- Frequency of 1 Hz means that there is 1 cycle per second.
  - 1 kilohertz (kHz) means 1000 cycles/sec.
  - 1 megahertz (MHz) means 1 million cycles/sec.
  - 1 gigahertz (GHz) means 1 billion cycles/sec.
  - 1 terahertz (THz) means 1 trillion cycles/sec.

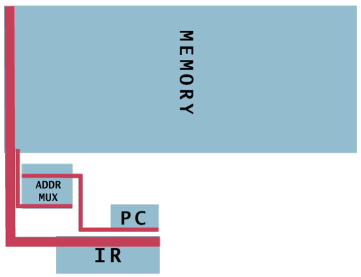
Heinrich Rudolf Hertz
(1857-1894)

Clocking Methodology

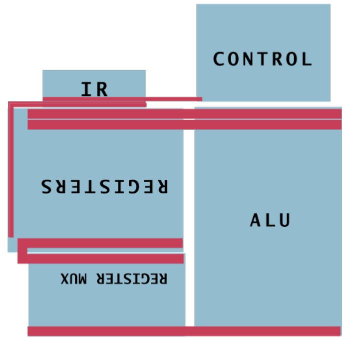
Two-cycle design.
- Each control signal is in one of four epochs.
  - fetch [set memory address from pc]
  - fetch and clock [write instruction to IR]
  - execute [set ALU inputs from registers]
  - execute and clock [write result of ALU to registers]



Datapath: Add

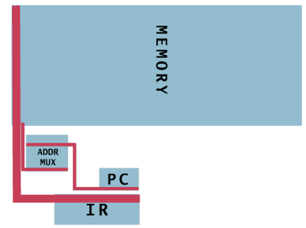


fetch

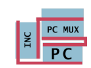


execute

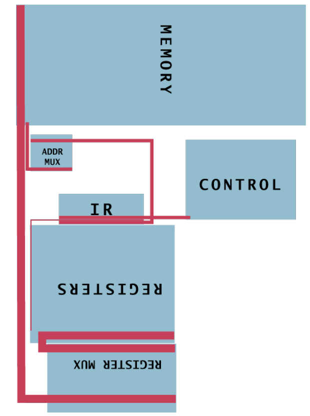
Datapath: Store



fetch



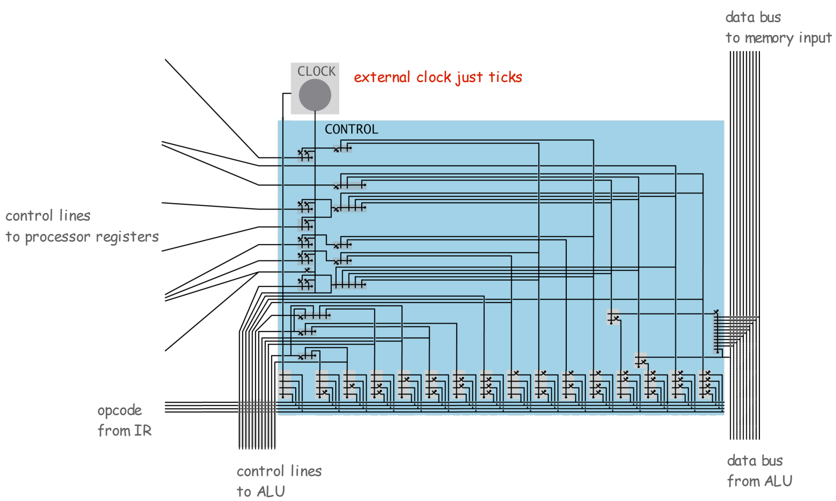
increment

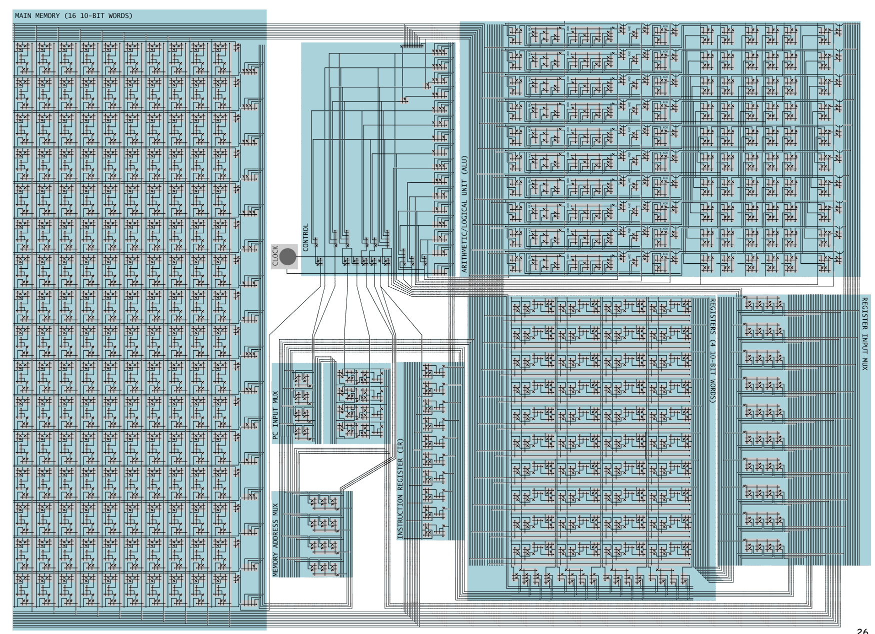


execute

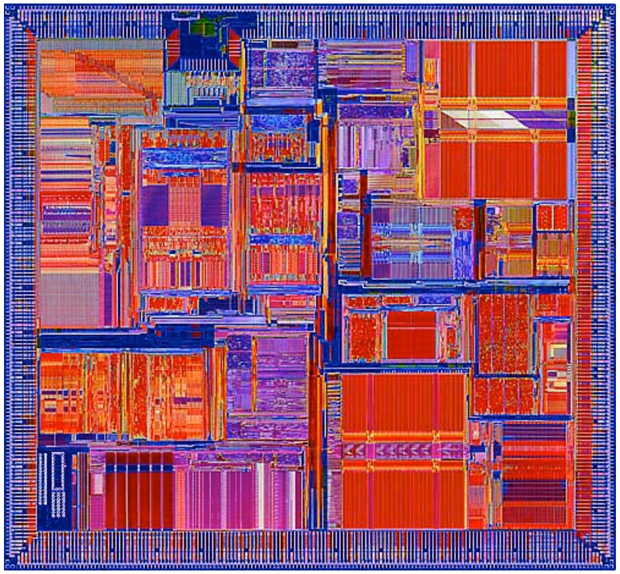
Control

Control. Circuit that determines control line sequencing.

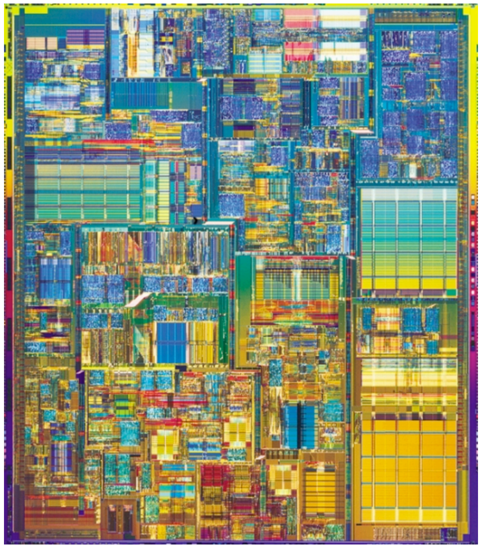




Real Microprocessor (MIPS R10000)



Real Microprocessor Chip (Pentium P4)



Layers of Abstraction

Abstraction	Built From	Examples
Abstract Switch	raw materials	transistor, relay
Connector	raw materials	wire
Clock	raw materials	crystal oscillator
Logic Gates	abstract switches, connectors	AND, OR, NOT
Combinational Circuit	logic gates, connectors	decoder, multiplexer, adder, ALU
Sequential Circuit	logic gates, clock, connector	flip-flop
Components	decoder, multiplexer, adder, flip-flop	registers, ALU, counter, control
Computer	components	TOY

History + Future

Computer constructed by layering abstractions.

- Better implementation at low levels improves everything.
- Ongoing search for better abstract switch!

History.

- 1820s: mechanical switches (Babbage's difference engine).
- 1940s: relays, vacuum tubes.
- 1950s: transistor, core memory.
- 1960s: integrated circuit.
- 1970s: microprocessor.
- 1980s: VLSI.
- 1990s: integrated systems.
- 2000s: web computer.
- Future: DNA, quantum, optical soliton, …